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TITLE INFLUENCE OF EXTERNAL WINDS AND CLOUDINESS ON THE TRANSITION LAYER ABOVE NOCTURNAL VALLEY DRAINAGE

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INFLUENCE OF EXTERNAL WINDS AND CLOUDINESS ON THE TRANSITION LAYER ABOVE NOCTURNAL VALLEY DRAINAGE

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1. INTRODUCTION

Studies of locally-driven drainage wind systems in a variety of valleys have demonstrated that, although these circulations are often dominated by the local thermodynamics, they are seldom completely decoupled from the ambient atmosphere above the ridge top. In the extreme, strong winds and turbulence in the ridge top regime may overpower the local circulation and eliminate the thermal gradients that drive it. However, even under more ideal drainage conditions we have observed differences in the depth, magnitude, and structure of the drainage wind that can only be the result of imposed influences of the external meteorology.

Past observations in mountain valleys during nighttime drainage conditions show the existence of a dynamically active transition layer between the locally-driven drainage flow and the upper free stream airflow (Davidson and Rao 1957, Intera 1976, Orgill and Schreck 1985). The height variations in this transition layer are analyzed with respect to external wind conditions, cloudiness, and weather. Data sets from the 1982 and 1984 Department of Energy's Atmospheric Studies in Complex Terrain (ASCOT) field experiments in Brush Creek Valley, Colorado are used in this analysis of the transition layer.

The field experimental data of the 1982 and 1984 ASCOT field programs were not designed specifically to study the transition layer above the nocturnal drainage. In this respect this study is of a preliminary nature and the results are directed toward assisting future field and computer modeling studies of the transition layer.

2. OBSERVATIONAL MODEL

Figure 1 depicts a simple observational model used for defining the transition layer as applied in this study. The base height of the transition layer (or depth of the drainage layer) is defined as that height where the wind speed decreases to a minimum and where the wind direction changes significantly (> 45°) from the downvalley direction. At times, the transition layer is more complicated, but these criteria apply in the majority of wind profiles examined in this study.

The purpose of this study is to document the impact of external wind conditions, cloudiness, and weather on the drainage wind and explore the mechanisms of interaction. We have used a number of diagnostic tools to achieve this purpose including the height of the transition base, along-valley streamlines, and cross valley wind components. The external wind field varies in response to a number of driving forces typical of mountainous terrain including synoptic pressure gradients modulated by the general topographic setting and thermally driven regional scale circulations resulting from the effects of the major features of the western slope of the Rocky Mountains. The transition layer is influenced by a variety of distortion and mixing processes including internal gravity waves, rotors and turbulence in the ambient flow, and eddies induced by winds across the ridges.

The role of cloudiness and weather on the transition layer depends upon sky coverage, cloud types, cloud height, and precipitation. These factors influence the transition layer through outgoing (longwave) radiation L^*, which is a function of surface and air (cloud) temperature, emissivity, precipitable water vapor, and clouds.

3. EXPERIMENTAL DESIGN AND DATA

This study uses tethered balloon, tower, radiation, and Lidar data from the 1984 ASCOT field program and tethered balloon and tower data from the 1982 ASCOT field program conducted in Brush Creek Valley in western Colorado. The Brush Creek Valley is a 25 km-long-valley that flows into Roan Creek Valley, 55 km NNE of Grand Junction, Colorado. The valley is oriented NW to SE, is 650 m deep at its lower end, has sidewalls with slopes of 30-40 degrees, and has a valley floor which drops 14 m per km.

Tethered balloon profiles were measured in the valley from seven sites in 1982 and eleven in 1984. However, not all these sites were useful for this study because of their locations and the fact that a number of wind and temperature profiles did not extend through the full valley depth. Thus data from three tethered balloon sites (ATDL, SNL, WPL) were used in 1982 and five (WPL, LANL, CSU, LLNL, PNL) in 1984. These sites were located near the center of the valley at different distances along its axis. Additional characteristics of the tethered balloon sites are discussed by Clements and Archuleta (1987).

Wind velocity, temperature, and net radiation data from

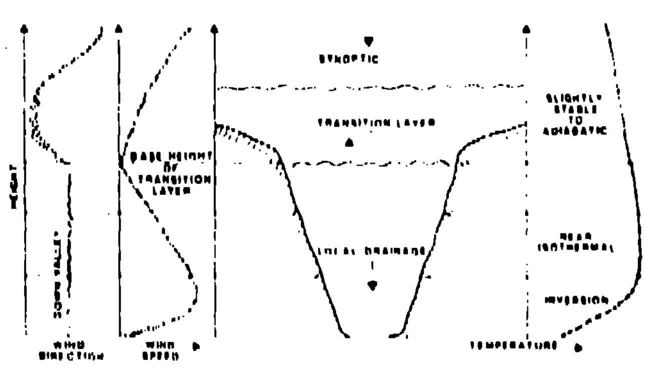

Fig. 1. Schematic diagram of the observational model indicating the relationship of the transition layer to observed wind and temperature profiles.

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three meteorological towers were used to help define the drainage nights of July-August 1982 and September-October 1984 and to evaluate drainage under different ridge wind directions and speeds, valley stability, and weather conditions. The measurement sites consisted of one tower on the valley floor and towers on the northeast sidewall and mesa top, 75 and 600 m above the valley floor, respectively. The instrumentation and data collection are described by Gudiksen (1985). Hourly-averaged data were obtained continuously between July 1982 and January 1985.

The effective outgoing (longwave) radiation L* was obtained from two Bowen ratio stations operated in the valley in 1984. These two sites were located in the valley approximately 3 km and 7 km from the mouth of the valley. The upward total hemispherical radiation (Lup) was measured with miniature net radiometers modified to include a black body cavity in place of the upper hemisphere. The temperature of the cavity was measured with a constant current source. Net radiation (Q*) was also measured with miniature net radiometers. The downward flux of long wave radiation (L down) was estimated as a residual from the computed radiation balance. At night, L* is the same as Q*. For additional details see Whiteman *et al.* (1987).

Information on cloudiness and weather was obtained from the hourly observations taken by the National Weather Service at Grand Junction, Colorado. Daytime observations of cloudiness and weather were taken in Brush Creek during the 1984 experimental period but these observations seldom extended into the nighttime hours. Cloudiness and weather conditions vary between Grand Junction and Brush Creek Valley but the Grand Junction data was the best continuous information available.

In the 1984 ASCOT experiments along-valley and cross-valley wind structure of the nocturnal drainage was measured by the Wave Propagation Laboratory's pulsed infrared Doppler lidar (Post and Neff, 1986). Measurements were made every half hour from 2300 MST to 1100 MST. These data have also been used to study the properties of the transition region in the valley.

4. ANALYSIS AND RESULTS

4.1. Cloudiness, Weather, and Radiation Data

The Angstrom ratio L*/Lup was selected as a radiation parameter for this study. This ratio expresses the leakage of long-wave energy through the atmospheric window caused by the incomplete emissivity of atmospheric gases. It is relatively large in dry air and in the afternoon (0.20 – 0.40), but when atmospheric emissivity increases because of cloud formation or increasing moisture, the ratio decreases to below 0.10 and approaches zero (Miller, 1981). The Angstrom ratio was calculated every half hour through the period September 16 to October 6, 1984 for the two valley stations. A plot of the average ratio from the two stations, tower winds and temperatures, Grand Junction cloud cover, and weather (Brush Creek cloud cover and weather when available) defined the nights of good, poor, and no drainage.

A summary of the average valley Angstrom ratio, PNL average base level transition heights between 2200 and 0600 MST, and cloudiness analysis is shown in Table I. There is not a good correlation between hourly values of the Angstrom ratio and the drainage layer except that relatively high ratios generally correspond with the deeper drainage layers. Most good drainage nights in Brush Creek have with average Angstrom ratios of 0.10 and above and cloud cover of less than 5/10. There were, however, drainage nights with lower ratios and at least two of these nights followed rainy periods (Sept 16-17, Oct 5-6) when residual moisture in the valley may have contributed to the lower ratios. An Angstrom ratio above 0.10 and clear skies was not always associated with good drainage conditions. Frontal passages and strong winds (Sept 27-28, 28-29) resulted in high ratios (≥ 0.15) but poor drainage. The effect of cloudiness on the transition height could not be evaluated properly because of the small data base and lack of nighttime cloud cover observations in Brush Creek Valley. However, there are some indications from the available data that broken to overcast cover of middle or high clouds (Ac, Ci, Cs) does not have a significant effect on the drainage layer, especially if the drainage develops prior to an increased cloud cover (Sept 30-Oct 1, 1984).

4.2. Ambient Wind Effects

The base height of the transition layer was estimated by using the criteria of the observational model. Heights were determined for each hour and each tethered balloon site for wind profiles that extended to ridge levels and higher. The transition heights were determined for six nights (Sept. 17-18, 19-20, 25-26, 29-30, 30-Oct.1, Oct 5-6) during 1984 and three nights (Jul 30-31, Aug 3-4, Aug 5-6) in 1982. Transition height estimates were limited to 3 to 6 a night in 1982 because of the limited height of the wind profiles. In 1984, tethered balloon profiles did not commence until 2300 MST.

The transition base heights were correlated with an average wind speed and direction calculated between 600 and 700 m from each tethered balloon profile. Plots of transition height versus average wind speed, along-valley wind speed, cross-valley wind speed, were made to show which correlation best represented the data.

Figure 2 shows a scatter diagram of the average wind speed within the 600 and 700 m layer and the base height of the transition layer for five of the tethered balloon sites and for four 1984 experimental nights. The relationship between these higher level winds and the transition height is approximately linear with a correlation coefficient of .69 and standard error of estimate of .77 m. Correlations of the transition height with cross- and along-valley wind components, Froude number, and the cross-valley Froude number were no larger. The intercept for a zero ridge-top wind speed is interesting because it suggests that in

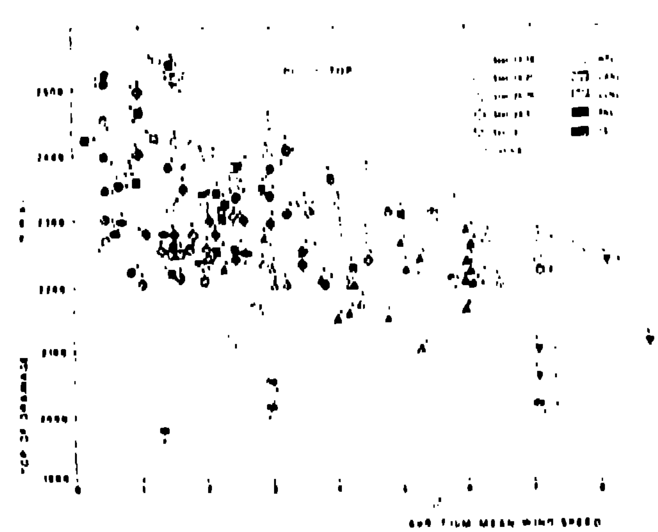

Fig. 2. Scatter diagram of the base of the transition layer plotted against the total wind speed at ridge altitude from the tethersonde runs. The plotted points represent 30 different categories of date and station using combinations of symbol shape and filling. Also the direction of the ridge-level wind is plotted with the symbol.

the absence of external influence the drainage wind will fill the valley.

An attempt to improve the correlation was made by using a Froude number based on temperature and wind data from the 600 to 700 m layer. Thus,

$$Fr = \frac{U}{NH} \qquad (1)$$

where U is the average wind speed in the 600-700 m layer, N is the Brunt-Vaisala frequency, and H is 100 m. The Brunt-Vaisala frequency is calculated as

$$N = \left(\frac{g}{\theta}\frac{\Delta\theta}{\Delta Z}\right)^{1/2} \qquad (2)$$

where θ is potential temperature.

Tower data (Gudiksen, 1985) were used to extend this analysis to periods beyond the experimental nights of 1984. Temperature, wind, and net radiation data for the three meteorological stations were plotted with respect to time and height for 17 nights between September 16 and October 3, 1984 and 3 nights between July 30 and August 6, 1982. An hourly Froude number was calculated between 1500 and 1000 MST using equations (1) and (2), the temperature data from the valley sidewall tower, and ridge tower and the ridge wind speed. A data base of the tower derived Froude number and N, and PNL transition height data and the transition base height for the PNL tethered balloon site was constructed for eight nights. The transition height measured at the PNL site was used because it was near the tower sites. The tower Froude number and ridge wind velocity provided a method for estimating transition heights for selected non-experimental nights that showed indications of drainage conditions.

The results based on the tower Froude number and PNL transition height are shown in Figure 3. High wind speeds at ridge level and reduced stability in the upper altitudes of the valley are associated with low drainage depths. Strong down-valley winds appear to obscure local drainage winds because of the associated pressure gradients and turbulence. Up valley winds oppose the drainage wind and thus the results are more definitive. From Figure 3, the results suggest that an up-valley ridge

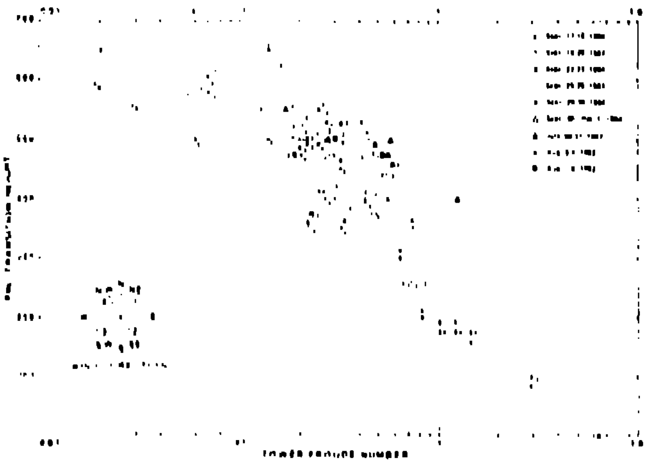

Fig. 3. Scatter diagram of the transition base height observed at the PNL Site plotted against the tower Froude Number. Ridge level wind directions are indicated by numerals plotted beside the symbols and are interpreted according to the key shown. Vertical arrows plotted near the symbol suggest that the value is an upper bound (downward arrow) or lower bound (upward arrow).

wind speed of 8 to 9 m/s (tower Froude number = 0.3 to 0.6) is sufficient to totally dissipate drainage conditions. The present data base is not adequate to determine what maximum cross-valley ridge wind is sufficient to eliminate the drainage wind.

The correlation between the external wind above the valley and the transition height does not explain all the variation in the transition height. Only about 47.5 of the variance is accounted for by the external winds. Thus other physical mechanisms must be contributing to the height variations.

4.3. Along-Valley and Cross-Valley transition layer circulations

The transition layer is displayed in Fig. 4 by means of streamlines in the vertical plane that is oriented along the valley axis. The stream function is derived from doppler lidar measurements of the along-valley wind component with a resolution of 300 m along valley, and 0.4 degrees of arc in the vertical and cross valley directions. The abscissa in Fig. 4 is expressed in terms of (300 m) range gates up-valley from the lidar site which is 4 km from the valley mouth. Hence the cross sections cover a length of Brush Creek from about 10 km to 6 km above the mouth. The stream function at a given range gate is derived by integrating upward the velocity values from the scan in the valley center using

$$\psi_i(Z) = \int_0^Z u_i(\zeta)d\zeta \qquad (3)$$

The plots in Fig. 4 are numerically interpolated isolines of ψ for selected hours on each of four nights taken from an ensemble of plots that includes hourly observations between 2300 and 1000 MST. The three nights with upvalley winds at ridgetop show remarkably similar streamline patterns. Apparent subsidence is consistent through most of the observed length of valley but is organized in a multi-cellular pattern. It should be noted that this stream function displays a three-dimensional flow as a two-dimensional representation. An apparently subsiding streamline merely reflects enhanced volume flux downwind and below the point of observation. This calculation does not distinguish true subsidence from lateral volume flux into the plane of observation (e.g. from tributary canyons).

The axis of maximum ψ represents the top of the drainage layer or base of the transition layer as defined in Section 2. In this field we see that there is about 150 m of weak velocity gradient above and below the axis. This region comprises the longitudinal circulation cells of the transition layer. The drainage wind below these cells appears to strengthen systematically in the down-

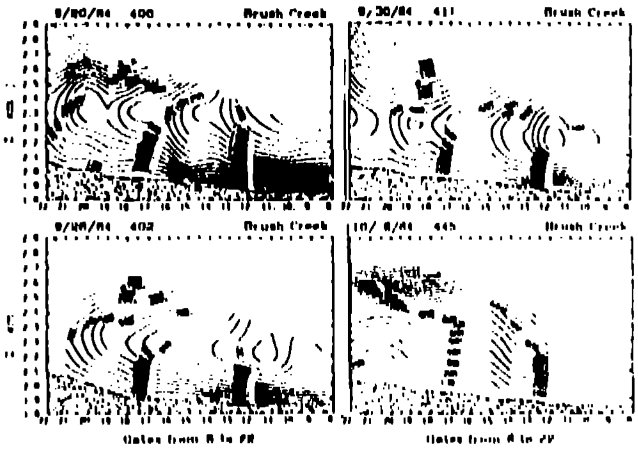

Fig. 4. Along valley streamline pattern for a representative hour from each of four nights.

Date 1984	Experiment	*Average PNL Drainage Depth	Valley L*/Ll Average	Valley L*/Ll Range	Grand Junction Cloud Cover (Tenths) Average	Grand Junction Cloud Cover (Tenths) Range	Cloud Types	Brush Creek Weather
Sept. 16-17		(≤550)	0.06	0.12-0.03	<1	0-3	Unknown	
17-18	0	580	0.13	0.14-0.11	0	0	None	
18-19		(≤575)	0.11	0.14-0.08	2	0-8	Ci	
19-20	1	530	0.12	0.13-0.11	4	0-7	Cb,Ae,Ci	
20-21		None	0.06	0.11-0.03	8	4-10	Cb,Sc,Ac,Ci,Cs	Rw-;Thunderstorms(T)
21-22		(≤300)	0.08	0.11-0.03	5	0-10	Cb,Cu,Ac,Ci	Rw-;T;Weak FROPA
22-23		(<200)	0.12	0.15-0.09	3	0-7	Cu,Ac	Windy;SW Winds
23-24	2A	None	0.08	0.12-0.04	3	0-8	Sc,Cu,Ci,Cs	Windy; SE Winds
24-25		None	0.10	0.19-0.04	6	0-10	Sc,Ac	FROPA
25-26	3	400	0.13	0.18-0.10	8	1-10	Ac,Ci,Cs	
26-27		(<450)	0.07	0.13-0.04	5	2-10	Sc,Ac,Ci	
27-28	4	None	0.15	0.17-0.08	2	0-4	Sc	FROPA;Windy NW Winds
28-29		None	0.19	0.20-0.18	0	0	None	Windy NW Winds
29-30	5	490	0.17	0.19-0.15	0	0	None	
30-Oct. 1	6A	<260	0.09	0.16-0.02	9	6-10	Cb,Ci,Ac	Rw-;T;Squall Line
1-2		None	0.02	0.06-0.01	10	9-10	Sc,Cu,Ac	T;Rain
2-3		(<475)	0.13	0.16-0.06	7	4-10	Sc,Ac,Cs,Ci	
3-4		None	0.02	0.05-0.02	10	10	Sc	Rain
4-5		None	0.03	0.04-0.01	10	10	Sc,Ac	Rain
5-6	7	<170	0.05	0.08-0.02	5	0-9	Sc,Ac,Ci	RW-;T

*Average PNL Drainage Depth- Average between 2200 MST and 0600 MST
- Heights within ( ) are estimated from Tower Froude number.

Table I. Average PNL Drainage Depths, Valley Average Angstrom Ratio, Grand Junction Cloud Cover and Types and Brush Creek Weather

valley direction and shows little sign of undulations. On October 6 (Fig. 4d) the ridge top wind was down valley, parallel to the drainage, so there is no reversal in the vertical gradient of ψ. There is an apparent change in character near the ridge line, where the external wind is stronger than that within the valley. Also, there is a suggestion of vertical undulations of the drainage streamlines.

Cross-valley circulation is a major way for the ambient wind field to be imposed upon the valley drainage domain. There are a number of mechanisms that could produce interactions at various intensities, and most of these would present a characteristic signature in the vertical profile of the cross-valley velocity component. We have selected cross-valley wind profiles from tethersondes as our diagnostic parameter for this analysis. Frictional separation of the boundary layer can produce a variety of cross-valley circulations, particularly for steep walled valleys. Lee *et al.* (1981) show wind tunnel results in which a major circulation fills a sinusoidal valley with a width to depth ratio of 3.7, similar to Brush Creek. For wider, shallower terrain such a dramatic separation eddy is not observed. The top of the Brush Creek sidewalls are quite sheer cliffs; and certainly some separation occurs, creating a wake of a few hundred meters depth near the ridge level. This should enhance mixing in the transition region when a cross valley component of more than a few meters per second is present in the ambient flow. During the cases that we have analyzed the atmosphere within and above the valley is stably stratified, and this gives rise to another class of cross valley circulation phenomena, internal waves. Lee *et al.* (1987) describe the character of wave induced cross valley circulations in terms of the ratio, λ/W, the wavelength of the internal wave divided by the ridge-to-ridge width of the valley. When λ/W is small, short waves will separate at the ridge and travel across the top of the valley, contributing, perhaps, to the fluctuations within the frictional wake. When λ/W is much larger than unity, separation will again occur at the upstream ridge, and the ambient flow will skip across the valley, leaving the internal domain somewhat undisturbed. However when $\lambda/W \approx 1$ the lee-wave pattern will be in resonance with the terrain shape, and the ambient flow will readily invade the valley. Another mechanism we suggest is upwelling in a form very similar to wind driven circulation in a body of water. If the conditions aren't appropriate for either direct injection of ambient air (e.g. lee-wave resonance) or vigorous entrainment at the transition layer interface, then the ambient wind flows across a decoupled volume of cold, dense valley air. Stresses induced at the interface will create a circulation within the dense fluid with upwelling at the upwind side of the valley.

The mass flux in the valley as revealed by streamlines in the x-z plane depends on a cellular structure in the transition region. Circulation cell centers and the areas of subsidence are distributed all along the segment of the valley that we studied but there were a few sites of preferred occurrence. The 0.6 km segments between range gates 21-19 and 17-15, for example, showed an enhanced frequency of apparent subsidence (mass influx).

We have looked for evidence of some of these mechanisms in profiles of cross valley wind component from two tethersondes, the Los Alamos Site 10 km above the valley mouth and the Pacific Northwest Laboratories site near the valley mouth. The valley is wider at the PNL site, giving us a chance to observe differences due, perhaps, to different λ/W values. Figure 5 shows profiles for the two sites for three nights along with postulated circulations that would produce these characteristic profiles. The PNL site seems to have more vigorous circulations than the Los Alamos tethersonde site with some suggestion of additional shallow induced circulations below the main one.

Cross valley circulations of magnitudes between 10 and 200 m^2/s appear to be induced by ambient flow across the top of the valley. If these circulations operate in a helix as the drainage flow travels down valley we would expect a circulation of about 10^5 to 10^6 m^3/s over a 10 km length of valley. This is the same order of magnitude as the drainage flux down the valley.

6. CONCLUSIONS

An analysis of the base height of the transition layer above nocturnal drainage in Brush Creek Valley during nine nights of the 1984 and 1982 ASCOT field program indicates that the transition height varies with the above valley external wind speed and direction, rotors and eddies, and to a lesser extent with cloudiness and gravity waves.

The external winds above the drainage layer account for 47.5% of the variance in the transition height. Rotors and eddies may account for most of the remaining variability.

The streamline patterns of Fig. 4 have the potential of distorting a material surface that may exist within the valley. Vertical velocities of 0.5 m/s or more exist over about 0.5 km segments of the valley length. Air passing through this system can change altitude by 50–200 m in the 5 to 10 minutes it would take to traverse a particular cell of the pattern.

The cross valley circulations are qualitatively consistent with observations in wind tunnels and stratified towing tanks for similar geometry and flow conditions. The most common circulation is a shear-induced helix created when the ambient flow separates at the upstream ridge and flows across the top of the cold dense valley air. This should distribute tracer material of pollutants throughout the confined valley regime fairly effectively. On one night the cross-valley flow appears to follow the terrain quite well at both the LANL and PNL sites.

The implication of these results is important with respect to how the dynamic and variable transition layer affects the nocturnal valley mass flux or the drainage strength. The results suggest a method for estimating average transition heights and drainage strength for non-experimental nights during the period July 1982 to January 1985.

Future modeling of drainage winds should incorporate the external wind effects and cloudiness. Future field experiments on drainage conditions should be designed to take continuous observations of wind and temperature profiles, cloud and weather observations, and long-wave radiation during all weather conditions in order to obtain a better data base on the variation of the nocturnal transition layer.

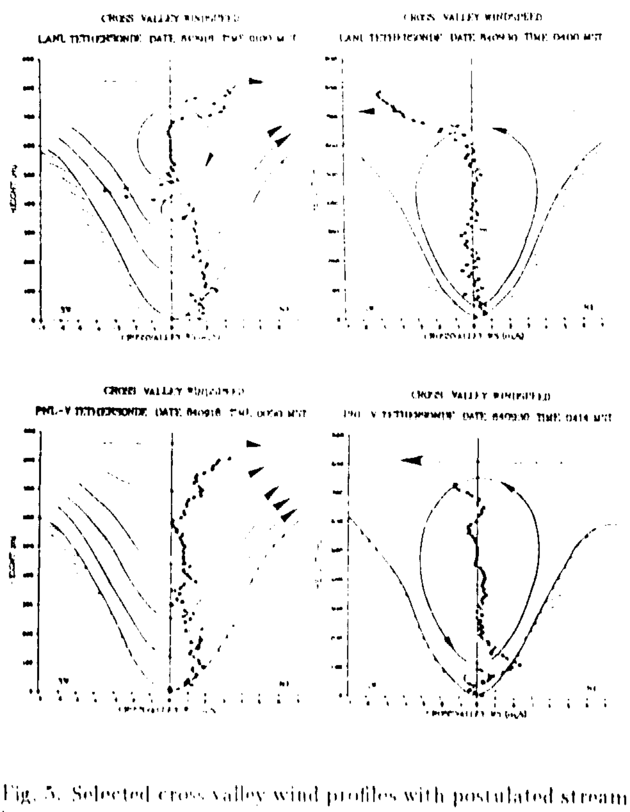

Fig. 5. Selected cross valley wind profiles with postulated stream line patterns that would be consistent with the profiles.

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